Application of Climate Impact Metrics to Rotorcraft Design

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Multiple metrics are applied to the design of large civil rotorcraft, integrating minimum cost and minimum environmental impact. The design mission is passenger transport with similar range and capacity to a regional jet. Separate aircraft designs are generated for minimum empty weight, fuel burn, and environmental impact. A metric specifically developed for the design of aircraft is employed to evaluate emissions. The designs are generated using the NDARC rotorcraft sizing code, and rotor analysis is performed with the CAMRAD II aeromechanics code. Design and mission parameters such as wing loading, disk loading, and cruise altitude are varied to minimize both cost and environmental impact metrics. This paper presents the results of these parametric sweeps as well as the final aircraft designs.

I. Introduction

ROTORCRAFT and other V/STOL aircraft have the potential to increase throughput in the National Airspace System (NAS) without requiring significant additional infrastructure at airports; however, air pollution is becoming increasingly regulated in industrialized nations, so new rotary-wing aircraft will need to be designed for minimal environmental impact.[1,2] In Europe, total CO_2 emissions by airlines were capped in the year 2012, with other emissions likely to follow. No such regulation has been enacted in the US, but may be in the future. If aircraft operators are limited in the amount of emissions they can legally produce, they will require designs that are not only efficient in terms of traditional metrics such as fuel burn and maintenance costs, but are also environmentally friendly.

A major conclusion of Ref. 2 was that replacing a significant portion of the regional jet traffic in the NAS with civil tiltrotors (CTR) could reduce future air traffic delays by more than 50 percent. Several NASA studies in the past decade have examined multiple rotorcraft configurations for large civil transport missions. These studies have largely concluded that a CTR is the best rotorcraft option for transporting payloads of approximately 100 passengers over ranges of around 1,000 nm.[3,4] Refinements to CTR designs have been the subject of multiple past and current studies.[5,6]

Environmental performance, particularly from an emissions standpoint, has been largely overlooked up to this point in rotorcraft design. Worldwide, aviation accounts for approximately 5% of all anthropogenic sources of radiative forcing (RF), a measure of the atmospheric effects of various pollutants.[7] If rotorcraft are to become a large part of the civil aviation fleet, they have the potential to make a substantial contribution to aviation's overall climate impact. There are multiple existing metrics that can be used to evaluate the effects of combustion emissions on the environment. Metrics specifically targeted at evaluating aircraft emissions are also becoming available.[8,9]

The purpose of the current study is to evaluate the environmental performance of a large CTR and of a similarly sized conventional helicopter (*the final paper may also include a compound helicopter, but this is to be determined.*). In addition to environmental performance, the aircraft will be evaluated for both minimum fuel burn (generally corresponding to direct operating cost) and minimum empty weight (generally corresponding to airframe purchase cost). While future rotorcraft will likely be designed to balance operating costs, purchase costs, and environmental performance, this study will separate them in order to show the effects of designing to different metrics.

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II. Background

A. Environmental Impacts

Designing rotorcraft for minimum environmental impact from an emissions standpoint is a fairly new area of research, though the impacts of fixed-wing aircraft have been studied for decades.[7] There is significant uncertainty in many of the metrics that can be used to evaluate the effects of emissions. Figure 1 shows the cause and effect chain linking aircraft emissions to atmospheric changes and ultimately societal impacts.[10] Effects near the top of the figure are relatively easy to quantify, but have little bearing on public policy and are thus not very useful for evaluating aircraft concepts. Effects near the bottom of the figure are much more difficult to accurately quantify, but are much more relevant to public policy. Any metric that is used to evaluate new rotorcraft concepts should balance uncertainty with relevance as much as possible.

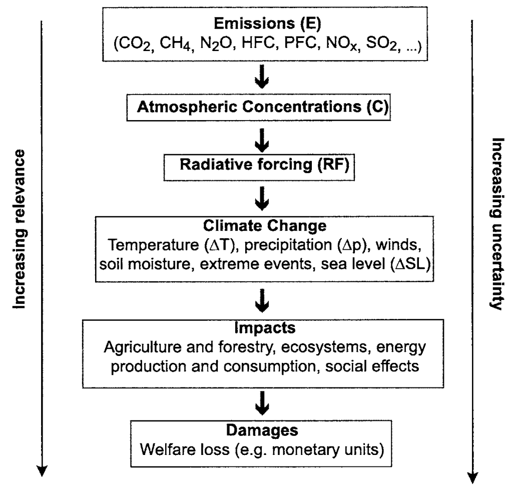


Figure 1. Cause-effect chain for climate change induced by aircraft emissions, reproduced from Ref.10.

In addition to choosing metrics that are relevant to current or future public policy and that have acceptable levels of uncertainty, it is desirable to use metrics that account for all relevant aircraft emissions, rather than a single species. Figure 2 shows the radiative forcing for the primary emission species produced by aircraft in 2005.[11] Note that the impact of NO_x emissions is of a similar magnitude to that of CO_2, but there is considerable uncertainty in the values shown in Fig. 2.

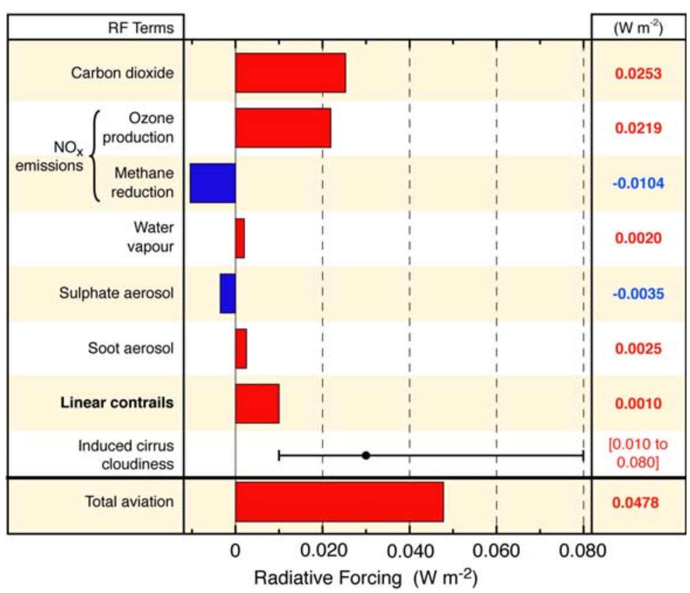


Figure 2. Components of RF due to various aircraft emission species, reproduced from Ref. 11.

Several environmental metrics were considered to measure the effects of rotorcraft emissions for this study. Of the available metrics, three were identified with high potential for evaluating rotorcraft concepts. In general, these metrics are well defined and have relatively wide acceptance in industry, public policy, or academia. These metrics, along with their advantages and disadvantages are described below.

(*The final study will likely use all three of these metrics. Initial results for the third metric, Average Temperature Response, are presented in this abstract*)

1. European Union Emissions Trading Scheme (EU ETS) Credits

The Emissions Trading Scheme is the system in place in the European Union to curb the effects of greenhouse gas emissions on global climate change.[12] Initiated in 2005, the ETS places limits on the amount of carbon dioxide that can be produced by large polluters such as energy and industrial installations in the EU. The ETS was extended to the aviation sector in early 2012.[13]

Under the ETS, each member nation has an emission cap which is used to allocate allowable carbon emissions to their industrial operators. Operators that do not use their entire allocation can sell their unused "carbon credits" on the open market, while operators exceeding their allocation must purchase credits on the market. The price of carbon credits for the current phase of the ETS has varied widely, ranging from below €10/tonne CO_2 to over €30/tonne CO_2.[14]

The main advantage of using ETS credits as a metric for rotorcraft designs is that this metric is easy to accurately compute and tie to direct operating cost. Total fuel burn translates directly to CO_2 produced, which can be used to determine the cost of operation in terms of carbon credits. Additionally, ETS credits are the only metric that can be tied to current aviation policy. This metric has two main disadvantages. First, the ETS only accounts for CO_2, while combustion engines produce several additional types of greenhouse emissions. Plans to include additional emissions in the ETS have been drafted, but are not yet implemented.[15] The second disadvantage is that volatility of the carbon trading market makes accurately predicting the future price of carbon credits difficult.

2. Global Warming Potential (GWP) and Equivalent CO_2 (CO_2-eq)

Global Warming Potential quantifies the amount of heat trapped by a particular emission species in terms of radiative forcing (RF), and expresses it in terms of the equivalent mass of a reference species (typically CO_2) that would have the same warming effect.[16] GWP can then be used to calculate the equivalent mass of CO_2 (CO_2-eq) emitted by a particular process (such as an aircraft mission) as long as the quantities of the various emission species are known. CO_2-eq expresses the contributions of multiple pollutant species as a single value—the equivalent mass of CO_2 that would have the same warming effect as the total pollutants emitted.

CO_2-eq is currently the accepted metric for determining total greenhouse gas emissions for nations that have signed the Kyoto Protocol, which sets reduction targets for six greenhouse gases: carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride.[17] The widespread acceptance of GWP makes it an attractive option for evaluating rotorcraft concepts, as does the ability to include multiple emission species in CO_2-eq. The Kyoto Protocol, however, does not explicitly target aviation emissions, so there is no defined method to compute CO_2-eq for rotorcraft. Also, the GWP of NO_x is highly dependent on altitude, so the mission profile affects its calculation. While variation with altitude adds fidelity to the metric, it also adds a source of uncertainty.[18]

3. Average Temperature Response (ATR)

Average Temperature Response is a recently developed metric that specifically targets aircraft emissions. The purpose of ATR is to assess the relative performance of aircraft concepts with respect to climate change. This metric is measured in terms of global mean temperature change caused by operation of a particular aircraft. ATR can be used with a number of different climate models, but simple linear climate models are appropriate for conceptual design of rotorcraft.[8]

Like GWP, the ATR metric is based on the RF generated by each emission species. The total RF for all emitted pollutants is used to calculate the global temperature response. The use of an altitude-varying climate model captures the effects of operating a particular aircraft at a multitude of operating conditions. In addition, ATR includes parameters such as usage rates and operating lifetime of the aircraft to determine the total climate impact that results from adding a particular aircraft to an operator's fleet.

The use of ATR for measuring the environmental impact of rotorcraft concepts has two main advantages. First, ATR is specifically targeted at evaluating aircraft emissions. Second, it is flexible enough to include multiple emission species and can utilize multiple climate models. A disadvantage is that ATR does not yet have widespread use in either the aviation or environmental community. As is the case with GWP, computation of ATR is subject to the uncertainty of the chosen climate model.

B. Computational Tools

1. *Sizing*

All of the sizing and design tasks were carried out using NASA's rotorcraft design code NDARC. NDARC is a conceptual/preliminary design and analysis code for rapidly sizing and conducting performance analysis of new rotorcraft concepts.[19,20,21] NDARC has a modular code base, facilitating its extension to new concepts and the implementation of new computational procedures. NDARC version 1.6 was used in this design activity.

A typical NDARC run consists of a sizing task, followed by off-design performance analysis. During the sizing process, point condition and mission performance are calculated and the aircraft is resized both geometrically and mechanically until the convergence criteria are met.

2. *Comprehensive Analysis*

Performance analyses for rotor optimization were conducted with the comprehensive rotorcraft analysis CAMRAD II.[22] CAMRAD II is an aeromechanics analysis of rotorcraft that incorporates a combination of advanced technologies, including multibody dynamics, nonlinear finite elements, and rotorcraft aerodynamics. The trim task finds the equilibrium solution for a steady state operating condition, and produces the solution for performance, loads, and vibration. The aerodynamic model includes a wake analysis to calculate the rotor non-uniform induced velocities. CAMRAD II has undergone extensive correlation of performance and loads measurements on helicopters.[23-30]

For this study, rotor performance optimization in CAMRAD II considered a single main rotor for each design, and the calculations for calibration of the sizing code rotor models consider an isolated rotor. Rotor performance was calculated using non-uniform inflow with rigid wake geometry in high speed cruise and free wake geometry in hover. Airfoil characteristics were obtained from tables representing advanced technology airfoils.

For calibration of the sizing code performance model, various sweeps were performed in both cruise and hover conditions. In hover, C_T/σ was swept through the range of expected thrust conditions. In cruise, forward and vertical thrust, along with forward velocity were varied through the expected envelope of operations for each rotorcraft design.

III. Approach

A. Aircraft Design Process

An iterative design process was used for this study and is illustrated in Fig. 3. Tasks of the design process utilizing NDARC are contained in the rectangular boxes, while tasks that used CAMRAD II are contained in the rounded boxes. Descriptions of the steps in the design process follow.

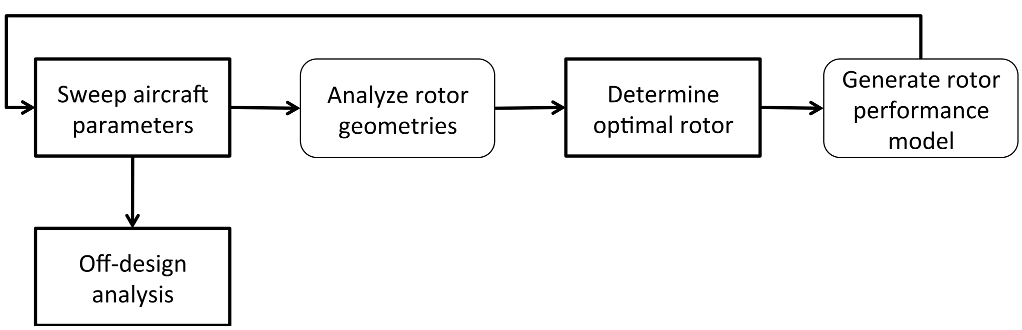


Figure 3. Iterative design process

1) <u>Sweep aircraft parameters</u>
   Aircraft characteristics such as wing loading, disk loading, and cruise altitude are varied in NDARC using a generic rotor model, resulting in a baseline configuration.
2) <u>Analyze rotor geometries</u>
   Rotor geometry is varied and simulated in CAMRAD II at the design flight conditions to develop a set of candidate rotors.
3) <u>Determine optimal rotor</u>
   Performance characteristics of the candidate rotor designs are used in NDARC to determine the best rotor for the design mission.

4) Generate rotor performance model
   Using the optimal rotor geometry, simulate various flight conditions in CAMRAD II to generate a math model of the rotor power consumption.
5) Sweep aircraft parameters 2
   With the rotor performance model determined, sweep aircraft characteristics again to arrive at a revised optimal configuration. If necessary, steps 2-4 can be repeated as many times as desired. For this study, the loop was only completed once for each aircraft.
6) Off-design analysis
   Once the aircraft configuration is determined, NDARC can be used to analyze different operating conditions and missions.

NDARC does not contain a formal optimization routine, so in order to minimize a particular objective function such as fuel burn or environmental impact, parameters must be varied and a new design generated for each set of input values. There are many design parameters that can be varied in NDARC, so care must be taken to properly choose a small subset of them. Otherwise, the number of design cases can easily become very large. For this study, the primary variables are wing loading, disk loading, and cruise altitude.

B. Performance Measures

Two types of performance metrics were used for this study: cost oriented and emissions oriented. Airlines or other operators will likely be primarily concerned with both airframe purchase price and operational costs. For this study, empty weight and fuel burn were used in lieu of a monetary cost metric. Initial purchase price of aircraft tends to correlate well with empty weight.[31] Increased global crude oil prices in the last several years have driven airline fuel costs up so that they now comprise approximately half of direct operating cost.[32] For this reason, fuel burn is a good indication of the cost to operate a particular design.

Emissions were measured using the Average Temperature Response (ATR) metric described in the Background section of this paper (*Again, the final study will likely use both of the additional metrics identified in the Background section, but that is TBD*). A thorough description of the method for calculating ATR is contained in Ref. 8, and the current study closely followed the process outlined therein. ATR expresses the environmental impact of a particular aircraft design in terms of the integrated global temperature change that would result from operation of the aircraft for a given amount of time. ATR can be expressed in relative terms, where the ATR for one design is divided by that of a baseline design. This allows for easy comparison between aircraft.

ATR employs an exponentially decaying weighting function when integrating the temperature response for the years after an aircraft ceases operation. This discounting is included so that long-term effects such as CO_2 warming do not necessarily dominate ATR. The rate of decay of the weighting function can be varied, and the effects of these variations will be shown in the results. A windowing function is also applied to ATR so that the metric only integrates effects over a specified length of time. The initial results use a window length of 500 years.

C. NO_x Calculations

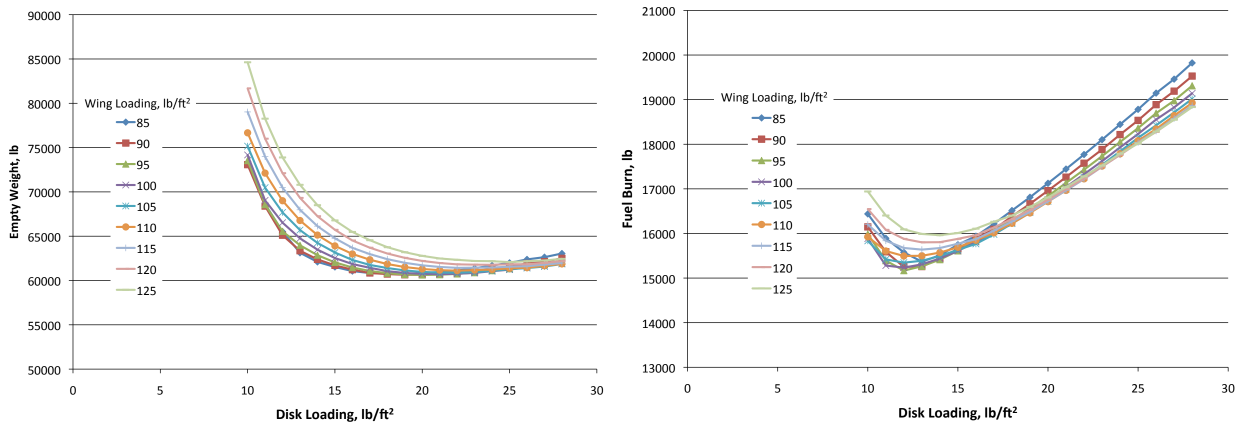
As shown in Fig. 2, oxides of nitrogen, including NO and NO_2 and collectively called NO_x, make a significant contribution to the environmental impact of aircraft. In order to determine this impact, it is necessary to know the quantity of NO_x emitted. Unlike CO_2 and other emissions species where the emitted quantity only depends on the amount of fuel burned, the mass of NO_x also depends on altitude and engine throttle setting. While turbofan engines have published NO_x emissions data and established methods for estimating variation with altitude, much of the data for the turboshaft engines used by rotorcraft is proprietary.[33,34] For the current study, an empirical approximation is used to estimate the NO_x "emissions index"—the quantity of an emission species emitted per unit of fuel. This approximation is based on emissions test data for multiple helicopter engines and is given in Eq. 1.[35]

$$EINO_x \approx 0.2113 * (SHP)^{0.5677} \tag{1}$$

$EINO_x$ in Eq. 3 is expressed in g/(kg fuel). SHP is the shaft horsepower output by the engine. (*There is considerable uncertainty in this model, so the final study will either use a more sophisticated model, or at least include upper and lower bounds on* $EINO_x$)

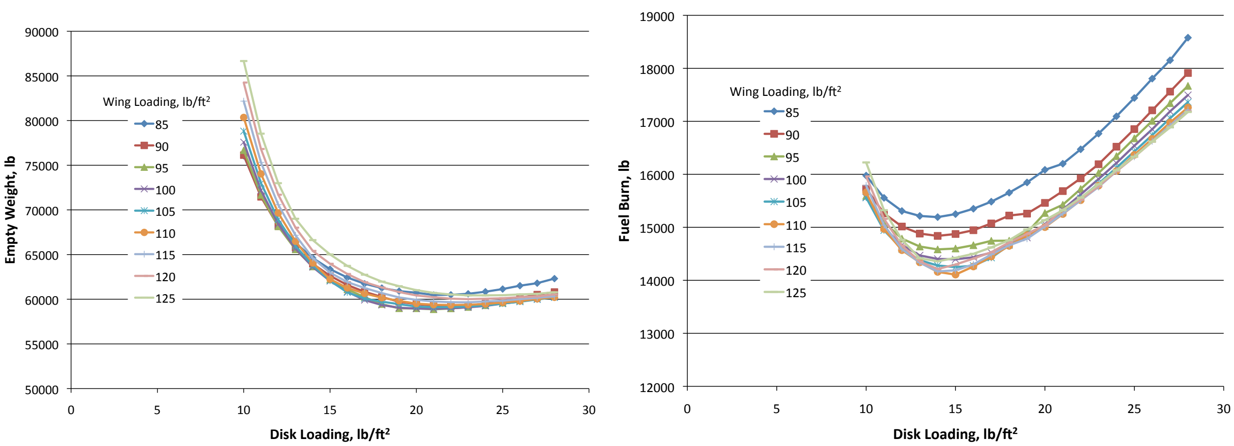
IV. Results

Initial results for sweeps of wing loading, disk loading, and cruise altitude are presented in Figs. 4 - 6 for the 90 passenger tiltrotor.



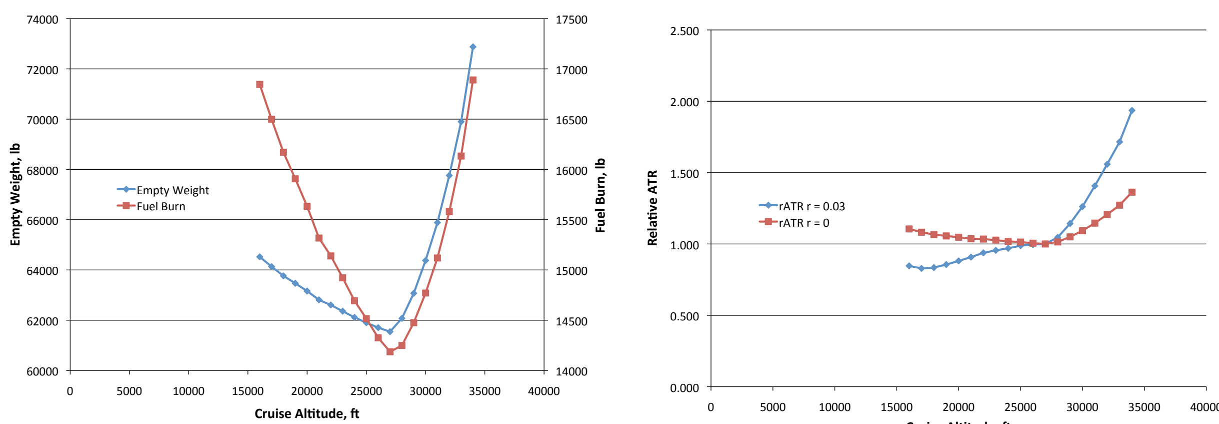
(a) (b)

Figure 4. Empty weight and fuel burn vs. disk loading and wing loading for 20,000 ft cruise altitude



(a) (b)

Figure 5. Empty weight and fuel burn vs. disk loading and wing loading for 28,000 ft cruise altitude



(a) (b)

Figure 6. Empty weight, fuel burn, and relative ATR vs. altitude for WL = 105 lb/ft^2 and DL = 15 lb/ft^2

Figure 4 shows that at a cruise altitude of 20,000 ft, a wing loading of 95 lb/ft^2 and a disk loading of 20 lb/ft^2 give the lowest empty weight, while wing loading and disk loading of 95 lb/ft^2 and 12 lb/ft^2, respectively give the lowest fuel burn. At 28,000 ft, WL = 95 lb/ft^2 and DL = 21 lb/ft^2 give the lowest empty weight, and WL = 110 lb/ft^2 and DL = 15 lb/ft^2 give the lowest fuel burn, shown in Fig. 5. Plots of ATR are not included for the constant altitude sweeps of wing loading and disk loading, because the trends closely follow those of fuel burn.

Figure 6 shows the result of an altitude sweep at constant wing loading and disk loading. Both empty weight and fuel burn are minimized at a cruise altitude of 27,000 ft, shown in Fig. 6a. ATR is shown in Fig. 6b and is expressed relative to a reference point. Here the reference point is taken to be the case at 27,000 ft, so rATR there is 1. As shown in Fig. 6b, the altitude for minimum ATR depends strongly on the discount rate *r* included in the time-decaying weighting function. When the discount rate is zero, the long-term warming effects of CO_2 dominate the temperature response, resulting in a minimum at the same point as minimum fuel burn. When the discount rate is 0.03, the short-term NO_x effects have a greater impact and result in a minimum ATR at 17,000 ft cruise altitude, despite increased fuel burn at that altitude.

V. Conclusions

This study examines the effect of designing rotorcraft for both minimum cost and minimum environmental impact. The preliminary data suggest that designing independently for minimum empty weight, fuel burn, and climate impact can result in three distinctly different designs. Additional parameter sweeps will be included in the final results to find the optimal combination of wing loading, disk loading, and cruise altitude for minimum fuel burn, empty weight, and environmental impact. Additionally, a conventional helicopter (and possibly compound helicopter) will be included to determine how its environmental performance compares to that of the tiltrotor for the same design mission.

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